

# TOWARDS A MULTI-INSTRUMENT ANALYSIS OF ATMOSPHERIC COMPOSITION IN FIRE DRIVEN ECOSYSTEMS

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## Abstract

Much research has gone into mapping the onset and spatial extent of fires using imager data from space. In addition, much progress has been made in the ability to characterize and trace biomass burning plumes with hyperspectral sounders. In this paper we investigate the feasibility of combining satellite measurements from different instruments to promote an improved and comprehensive understanding of pollution events.

## 1 INTRODUCTION

In recent decades, climate change assessment has become a major focus area in Earth systems research. This involves the identification and characterization of pollutant source and sink. A gas species that is considered to be an excellent tracer of atmospheric pollution is carbon monoxide (CO). It has a chemical lifetime of several weeks in the troposphere and is a precursor to both CO<sub>2</sub> and tropospheric O<sub>3</sub>. Measured and monitored over consistent spatio-temporal scales, CO can serve as indicator of pollution transport. A major source of CO worldwide is biomass burning (e.g., van Leeuwen & van der Werf, 2011). Satellite measurements have been instrumental in mapping the onset and horizontal extent of biomass burning events worldwide (e.g., Roy et al. 2008; Giglio et al. 2013). In addition, much progress has been made in characterizing the chemical lifecycle of biomass burning plumes as well as global trace gas patterns (e.g., Martin 2008; Hilton et al. 2012) using satellite soundings. However, it remains to be determined how these different satellite measurement sets can be used in synergy to provide a comprehensive view of pollution events.

Per annum, the majority of global burned area is in the grassland and savanna ecosystems of Africa (van der Werf et al. 2010). This is significant in light of predicted climate change for this continent. The expected 2–6°C temperature increase will significantly change environmental factors that determine the frequency and extent of biomass burning. Developing methods with which to analyze the carbon contribution from and ecosystem response to biomass burning in different meso-scale (or sub-continental) regions is therefore an important step forward. Specifically, a record of the composition and space-time distribution of fire emissions can give insight into ecosystem health (e.g., patterns in emission intensity and composition can indicate vegetation disturbance and changes in regrowth rate) and functioning (e.g., carbon uptake and/or accumulation as well as local changes in weather such as wind patterns and temperature inversion anomalies).

In this paper we aim to investigate the synergistic use of multi-instrument space-based measurements to improve our understanding of fire-driven ecosystems on a meso-scale. We are specifically interested in combining surface measurements from MODIS (Moderate resolution Imaging Spectroradiometer) – an imager well known for its capability to measure fire scars – and trace gas measurements from IASI (Infrared Atmospheric Sounding Interferometer) – a hyperspectral sounder with a spectral resolution that is high enough to measure atmospheric composition and structure at tens of layers along the vertical column. The study of complex Earth systems requires spatially and temporally consistent data with high accuracy and precision. Satellite measurements are, therefore, invaluable sources of data. There are four imager-hyperspectral sounder pairs currently operational in polar-orbit, which means a minimum of eight measurements per area per day. We will focus our present attention on MODIS and IASI. The former is on the Aqua platform (since 2002) in an afternoon orbit (local crossing time ~13h30), while the latter is on Metop-A (since 2006) in a morning orbit (local crossing time ~09h30). The retrieval of CO from IASI radiance measurements is well documented

(Illingworth et al. 2011b; Smith et al. 2011; Hurtmans et al. 2012). So is the evaluation of global CO trends (Worden et al. 2013), characterization of fire emissions (Clerbaux et al. 2009; Coheur et al. 2009; Turquety et al. 2009) and comparison with CO retrievals from other instruments (e.g., George et al. 2009, Illingworth et al. 2011a). Similarly, MODIS fire products are well published and widely applied (e.g., Boschetti et al. 2008; Chang and Song 2009; Roy et al. 2008; de Klerk et al., 2011; Giglio et al. 2013).

The main science questions of this research project are:

- Is there a correlation between imager-derived burned area estimates (e.g., from MODIS) and infrared sounder retrieved CO column amounts (e.g., from IASI) in meso-scale ecosystems with strong biomass burning seasonality?
- Given the limited sensitivity of hyperspectral infrared sounders to CO in the boundary layer, how can these space-borne measurements be used in meso-scale air quality monitoring?
- Can space-borne hyperspectral sounders measure, rather than model, the carbon contribution from meso-scale fire ecosystems? i.e., Are the current global-scale CO products from hyperspectral sounders good enough?
- Given the scarcity of in situ trace gas measurements (especially in under-developed regions), can we develop a different approach for evaluating the accuracy and precision of hyperspectral trace gas retrievals? Will a systems approach to data usage improve our confidence in the quality of space-borne measurements?

In this paper we first give an overview on methods and data used in Section 2, then discuss a set of initial results in Section 3 and conclude with lessons learned and a focus on future research in Section 4.

## **2 METHODS AND DATA**

Our main objective is to determine whether IASI CO retrievals can be used to map trends in atmospheric composition for meso-scale ecosystems that are prone to seasonal pollution events. We thus focus on and compare two ecosystems (or sub-regions) in the southern African region. They are the Mediterranean shrubland (or Fynbos) and Savanna woodland. Both regions display strong seasonality in biomass burning. The Fynbos has medium density fuel load, burns in the Summer months (Jan–Feb) with a flame length of 5–6m at a speed of 1–2km/h. It can burn for a couple of weeks in the mountains. Savanna, on the other hand, has light density fuel load, burns in the Winter months (Jul–Aug) with a flame length of 3–5m at a speed of 4–10km/h. It typically burns for a couple of days only. See Forsyth et al. 2010 for a more detailed comparison.

### **2.1 CO amount from a hyperspectral sounder**

A number of different IASI CO retrieval algorithms and products exist (Illingworth et al. 2011a, Smith et al. 2011, Hurtmans et al. 2012) but for the sake of simplicity here, we limit our analysis to one CO product, namely FORLI (Fast Optimal Retrievals on Layers for IASI). The daily CO values (profile mixing ratio and total column amounts) are available online at instrument resolution (~12km; <http://www.pole-ether.fr>). The FORLI retrieval algorithm (Hurtmans et al. 2012) is optimized to characterize global (not local) CO trends. However, the accuracy and precision of the IASI FORLI CO retrievals (IASI CO from here on) has been demonstrated to be good enough at meso-scale for the depiction of emission patterns from isolated large fire events (e.g., George et al. 2009). In addition to retrieved CO values, the FORLI product also includes retrieval by-products such as error and information content (as degrees of freedom) estimates. In this paper we use the degrees of freedom and CO column amounts (integrated across the vertical atmospheric column from surface to top of atmosphere) measured in units, molec/cm<sup>2</sup>.

### **2.2 Fire extent from a broadband imager**

One of the most widely applied and successful fire products of polar-orbiting imagers is burned area (BA) estimates. The high spatial resolution of imagers (sub-kilometer scale) makes accurate BA estimates possible for a range of local to global applications. One of the MODIS BA products is based on the Giglio et al. (2013) algorithm. This product shows strong agreement with in situ fire scar

measurements in South Africa (De Klerk et al. 2011). The Giglio et al. (2013) MODIS BA product (MODIS BA from here on) is available online (<http://www.globalfiredata.org>). MODIS BA is initially retrieved at native instrument resolution (0.5 km) but then aggregated to monthly BA (measured in units, Mha) per quarter degree grid cell.

### 2.3 Statistical methods

Colocation between imager and sounder data products were established by resampling the IASI CO retrievals to the MODIS BA product grid using the method described in Smith et al. (2013). The MODIS BA grid is a quarter degree equal-angle latitude/longitude grid from  $[-179.25^\circ, 89.75^\circ]$  in the North-West corner to  $[179.75^\circ, -89.75^\circ]$  in the South-East corner.

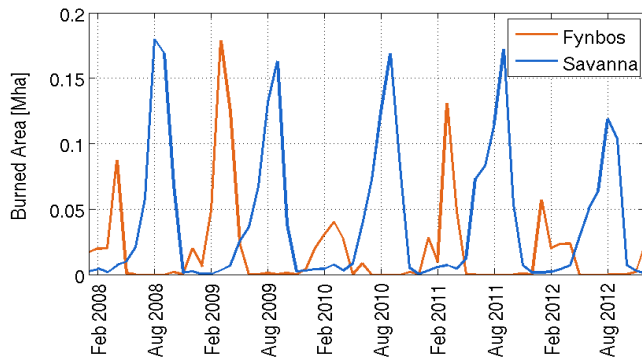
A five-year record (2008–2012), of collocated IASI CO and MODIS BA estimates was assembled. The MODIS BA product was used as distributed without any additional manipulation; this is the BA within a quarter-degree grid cell per month (thus 60 monthly averages for the five year period). BA is a static surface property and it is logically intuitive to sum or average the values over time. CO, on the other hand, is a highly variable atmospheric property. For comparison with MODIS BA, we therefore derived a number of CO aggregates to promote depth of analysis:

- Monthly total column CO: IASI CO values were first resampled into daily aggregates (e.g., mean and standard deviation) from which the monthly statistics were calculated; e.g., a monthly mean is the mean of the daily means. A minimum sample size threshold was applied to the daily aggregates to avoid situations where statistics are calculated for grid cells with too small a sample size. A (sub-)regional monthly aggregate was obtained simply by averaging across all grid cells in each demarcated (sub-)region; the Fynbos and Savanna sub-regions and southern African region.
- Normalized CO: This is a relative anomaly, calculated as the sub-regional (monthly total column) CO deviation from the regional (monthly total column) CO mean divided by the regional (monthly total column) CO mean (in units, percentage). This removes the regional seasonality from sub-regional monthly averages.
- CO peaks: These are calculated to emphasize seasonal biomass burning events, events that can otherwise be averaged out in the monthly aggregates. CO peaks were calculated by using only those IASI CO values that exceed a threshold of  $10^{17}$  molec/cm<sup>2</sup>. Daily aggregates of total column CO were calculated for each quarter degree grid cell in the southern African region. A seasonal frequency per grid cell was obtained by counting the number of daily averages that passed the threshold test. In other words, CO peaks are the number of days that CO exceeded a certain threshold (maximum 61) on a quarter degree scale. Two seasons were of interest in this paper; Summer (January–February) when Fynbos burns and Winter (July–August) when Savanna burns.

## 3 RESULTS AND DISCUSSION

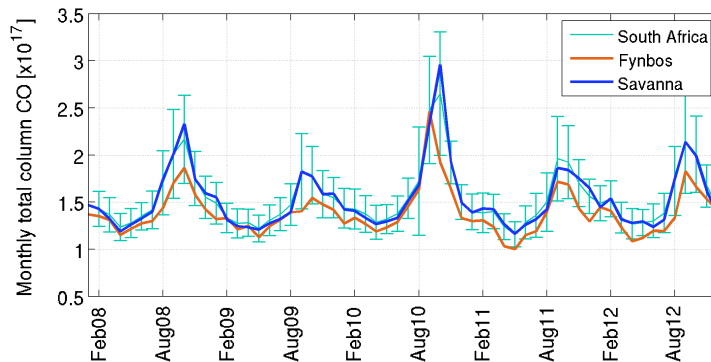
Worldwide, natural biomass burning contributes significantly to the portion of CO and aerosols (e.g. black and organic carbons) in the atmosphere (Giglio et al. 2010). It has been estimated that Africa contributes over 50% (52% over 1997-2009 van der Werf et al. 2010) of biomass burning emissions globally. Southern Africa is, therefore, internationally recognised as a focus area for atmospheric and climate change research (e.g. World Meteorological Organization, the Intergovernmental Panel on Climate Change, and the International Geosphere Biosphere Programme).

Within the southern African region, there are a number of different ecosystems prone to biomass burning. Characterizing the emissions and fire-impact of these systems is a major step towards understanding possible climate change scenarios on a sub-regional scale. Satellite measurements of surface and atmospheric ecosystem parameters (such as CO and burned area) offer unprecedented quality and consistency of information for in-depth analysis.



**Figure 1: Total burned area per month per sub-region (Fynbos in orange, Savanna in blue) derived from MODIS measurements (Giglio et al. 2013) for five years, from 2008 to 2012. The monthly totals for each sub-region were calculated as the sum of monthly burned area of all quarter degree grid cells in each sub-region.**

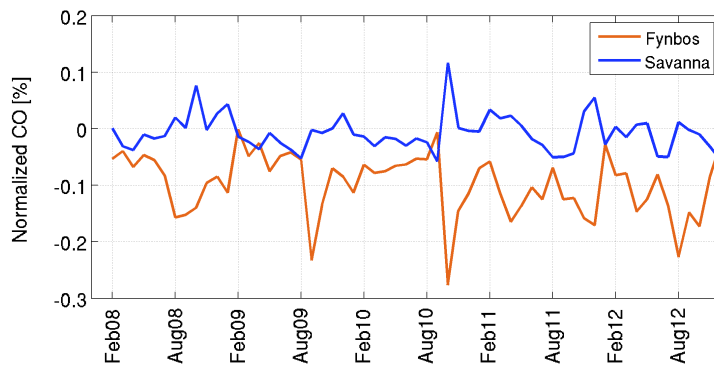
The Giglio et al. (2013) MODIS burned area product confirms the strong seasonality of biomass burning in both the Savanna and Fynbos sub-regions (Figure 1). Moreover this product confirms the typical May-September austral winter peak in fire activity in the Savanna (e.g. van Wilgen et al. 2004) as well as the November-March summer fire activity peak in the Fynbos (e.g. van Wilgen et al. 2010). In general, larger areas burn in the Savanna than in Fynbos, and this is likely due to the fact that the Savanna has a higher fire return interval (or fire frequency) of around three to seven years (e.g. van Wilgen et al. 2004) compared to that of 10-35 years in the Fynbos (van Wilgen et al. 2010; Wilson et al. 2010). However, note that the peaks in BA in 2009 indicate that biomass burning in the Fynbos can be as extensive as in Savanna for any given year. In addition to higher fire frequency, fires in the African Savanna tend to burn much faster and cover a great distance per hour than fires in the Fynbos (see Table 1; Forsyth et al. 2010). Man made fires are applied both by commercial and subsistence farmers in large parts of the Savanna which further increases the annual area burned for the Savanna biome.



**Figure 2: Monthly total column CO [ $\times 10^{17}$  molec/ $\text{cm}^2$ ] for each of the sub-regions, Fynbos (orange) and Savanna (blue), are plotted against the regional monthly total column CO (teal). For each regional monthly total column value, the standard deviation is added as an error bar to depict regional CO variation.**

Plots of monthly total column CO, at this spatial and temporal scale (monthly averages at quarter degree), show strong seasonality that is dominated by the southern hemisphere mixing (Figure 2). The southern hemisphere mixing is possibly dominated by the winter biomass burning patterns of the Savanna as this vegetation type covers a large proportion (~46%) of the southern African region. The Fynbos, in contrast, covers only 6% of the same region (Mucina & Rutherford, 2006).

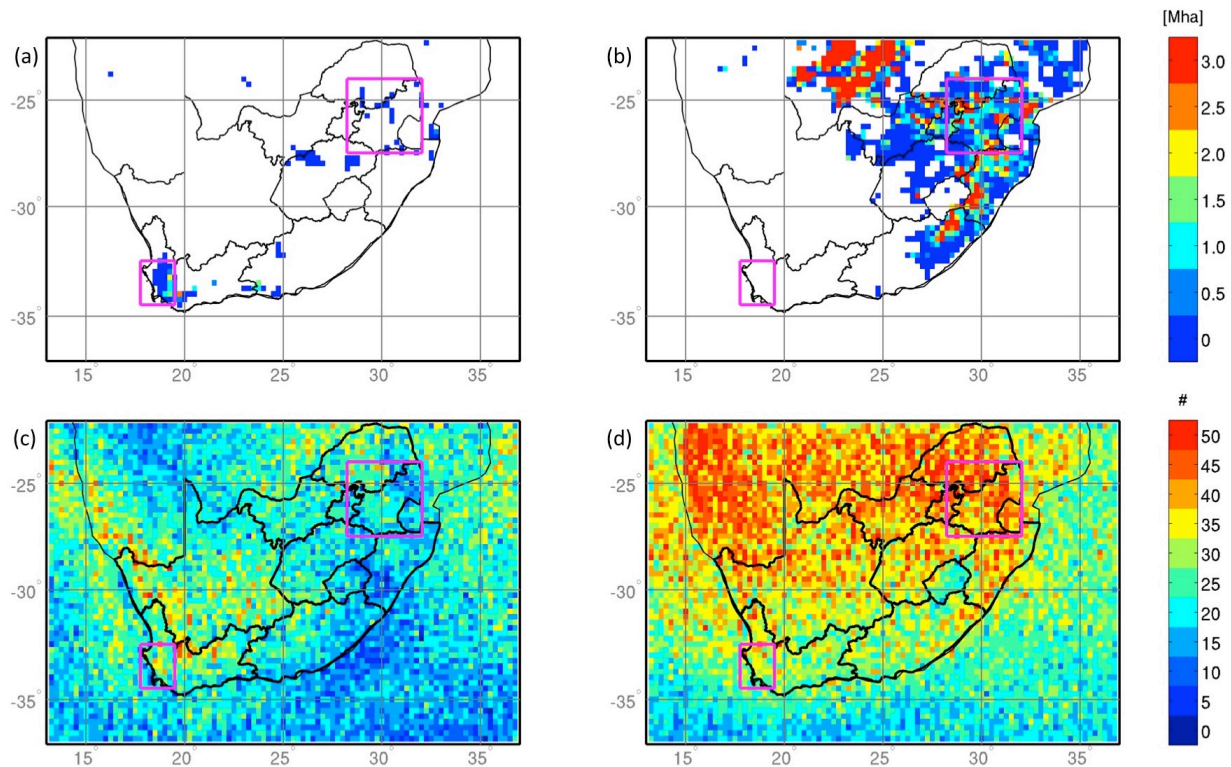
A standard method for removing the seasonality from measurements is to calculate the deviation from the seasonal average (see discussion of “normalized CO” in Section 2). For CO, we calculated a relative monthly value (sub-regional mean minus regional mean divided by regional mean) to depict anomalies in percentage. This is akin to the removal of ‘background CO values’ as done by Turquety et al. (2009).



**Figure 3: A five-year period (2008–2012) of monthly normalized CO for each of the sub-regions, Fynbos (orange) and Savanna (blue).**

The results in Figure 3 show a more sensitive response of IASI CO to sub-regional differences. For example, elevations in monthly CO due to Summer-time Fynbos biomass burning can now be seen as peaks the data in most years around February for Fynbos (orange line in Figure 3). The normalized CO data indicate a better match in seasonal patterns of biomass burning (burned area) and CO levels in both the Fynbos and the Savanna (compare the summer peaks in the orange data lines in figures 2 and 4 for the Fynbos, and the winter peaks in the blue data lines in Figures 1 and 3 for the savanna). Hyer et al. (2007) found that analysis of CO patterns at monthly temporal resolution resulted in a loss of important explanatory power relative to weekly or daily analysis. However, in the southern African region we are able to distinguish important patterns at the monthly time scale using normalized CO values.

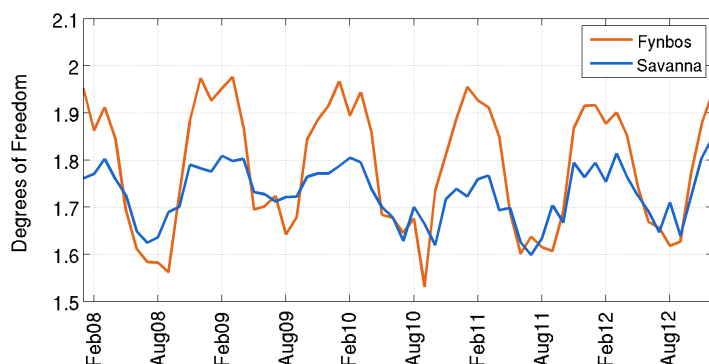
We now look at daily CO values that exceed empirically defined thresholds in order to obtain a finer temporal resolution, which we have termed ‘CO peaks’ (Section 2). Figure 4 shows peaks in daily CO in the Fynbos during the summer fire season along with the ‘plume’ to the northwest as the strong southeasterly winds blow the fire emissions offshore.



**Figure 5: Total MODIS burned area (Giglio et al. 2013) on a quarter-degree grid five of years (2008–2012) for (a) Summer (Jan–Feb) and (b) Winter (Jul–Aug). The CO peaks are displayed on the same grid for (c) Summer and (d) Winter.**

Note that during summer there are few to no peaks in daily CO over the Savanna sub-region. Figure 4 shows the very high frequencies of CO during the winter fire season in the Savanna sub-region, and indeed across most of southern Africa, which most likely again points to the impact of southern hemisphere mixing on CO patterns. This is mostly clearly seen by contemplating the arid, grassy, dwarf shrubland of the Nama Karoo that covers central South Africa, which doesn't produce sufficient fuel load to carry fires (Mucina & Rutherford, 2006) and so shouldn't show CO peaks at any season if a pixel's CO is purely due to biomass burning and other factors generated in the same pixel or very localized area. The Karoo does not support high human populations, major industry or major agriculture. Yet Figure 4 shows peaks of CO for this area in the winter. This points to the strong southern hemisphere mixing. This diversion of CO-laden air from areas that experience high levels of winter biomass burning is helped along by Hadley's High pressure system that covers the whole southern Africa in winter. As the pressure system drives the air downwards it drives the air from the interior plateau (much of which is covered by savanna) east-, south- and westwards to the coastlines, gaining momentum as it drops off the escarpment. Note the absence of CO peaks in Lesotho in Figure 4. Lesotho is known as the 'Mountain Kingdom' with an average height 1000m higher than the surrounding escarpment. The low frequency of CO peaks in this region (Figure 4d) can be explained by the high pressure system that prevents the CO-laden air from the escarpment to move upwards to the higher lying areas of Lesotho.

The average degrees of freedom (DFS) per month (a metric of instrument information content) per region is depicted in Figure 6 below. Despite differences in season and sub-region, the DFS is always greater than 1.5. This is high considering that the global minimum can get as low as 0.8 during high latitude Winter months (George et al. 2009). In addition to a high DFS, the background CO value is generally low for southern Africa due to the sparse and isolated pockets of industrial zones. This makes it possible to characterize sources of CO more easily than in the Northern Hemisphere where industrial zones are larger and denser and causes a relatively high background CO value. With a  $DFS \geq 1.5$ , a column CO amount can be retrieved with high confidence from IASI measurements.



**Figure 6:** IASI degrees of freedom (DFS) for CO averaged per month across five years (2008–2012) for two sub-regions (Fynbos in orange and Savanna in blue). DFS is a metric of information content. Note the strong seasonal patterns.

These results support the fact that IASI CO retrievals for this region can possibly be improved with a retrieval algorithm specifically optimized for regional and seasonal environmental conditions.

#### 4 CONCLUSIONS AND FUTURE RESEARCH

This paper describes a method for the synergistic use of measurements from two types of space-based instruments, imagers and sounders, for the analysis of seasonal biomass burning. The initial set of results presented here indicates that this approach holds great potential for providing a holistic analysis of pollution events and air quality on a regional scale. Our focus was aimed at describing atmospheric CO patterns for two sub-regions in southern Africa, both of which are affected by strong seasonal biomass burning cycles.

Based on lessons learned, our future research will include the following:

- Investigate whether the time of measurement influences daily and monthly trends for CO on a regional scale (i.e., quarter-degree resolution). IASI is on an AM orbit (local crossing time ~09h30 UTM). Given the strong anthropogenic nature of biomass burning sources in southern Africa, it

may be that CO retrievals from CrIS (Cross-track Infrared Sounder onboard S-NPP, which is on a PM orbit with local crossing time ~13h30 UTM) show a stronger correlation with MODIS BA products.

- Apply a comprehensive multi-parameter analysis using the methods developed in this paper. Hyperspectral sounders in space provide measurements with which to retrieve information about the atmospheric structure (e.g., temperature and water vapor profiles, cloud height and optical thickness, etc.), atmospheric composition (e.g., trace gas mixing ratios of O<sub>3</sub>, CH<sub>4</sub>, CO, and CO<sub>2</sub>) as well as Earth surface conditions (e.g., emissivity and temperature). A multi-parameter analysis will help shed light on the observed emission patterns and trends by incorporating measurements of the geophysical environment, e.g., boundary layer temperature inversions or emissivity changes. A strong correlation among different instrument retrieval parameters will additionally improve the confidence with which satellite measurements can be used in Earth surface.
- Investigate additional statistical methods for describing the chemical nature and geographic distribution of biomass burning emissions.
- Repeat this study with CrIS and IASI CO retrievals from the multi-instrument hyperspectral dual-regression (DR) retrieval algorithm (Smith et al. 2012, Weisz et al. 2013). The multi-instrument capability of the DR method allows an analysis of CO patterns on a daily time-scale (given the recent launch of IASI on Metop-B there are at least six DR retrievals per area per day). This could help characterize regional emissions on shorter time-scales immediately following a fire event. Moreover, a comparison with the FORLI CO product will shed light on the sensitivity of space-based CO measurements to retrieval methods.

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